PROTECTION DEVICES AND DEVELOPMENT TOOLS FOR REDUCING FOOT AND LEG INJURIES IN FRONTAL CRASHES

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ABSTRACT

Several accident statistics point out that the lower extremities are the second most endangered body region in a frontal crash. Especially the area of ankle and foot is endangered most.

PARS has designed protection devices for the feet as well as new simulation tools like sled tests with dynamic footwell intrusion.

PARS performed crashtests with different crash severity and car types. These data were used to investigate injury mechanisms for the occupant as well as to develop protection devices for the foot area.

Moreover the data were used to define the demands on a dynamic footwell intrusion system for the sled test facility.

The protection devices were ranked with the use of an simulation model, based on a worst case scenario.

The footairbag, which comes out of the investigation is the most promising concept with a proven reduction potential in a sled test up to nearly 80%.

DURING THE LAST YEARS the passive safety in the automotive field has become very important.

With the introduction of frontal airbags the number of fatalities were significantly reduced.

In the second step the introduction of the thorax airbag saves many lives in a lateral impact and nowadays the combination with a separate head protection (head-airbag) will once more reduce the number of killed occupants.

Now for future work it is not only the aim to prevent the occupant from sustaining live threatening injuries. Moreover he should be prevented from injuries which will reduce his quality of life.

LITERATURE REVIEV AND INJURY ANALYSIS

ENDANGERED BODYREGIONS - From the accident statistics it can be seen that the lower extremities are the second most endangered body region, directly following the head (AIS 2+) [Morgan, 1991]. The lower extremities, this means pelvis, femur, knee, tibia, ankle and foot, are not endangered with the same risk. Figure 1 shows the distribution in frontal crashes within the lower extremities [see references 1-6].

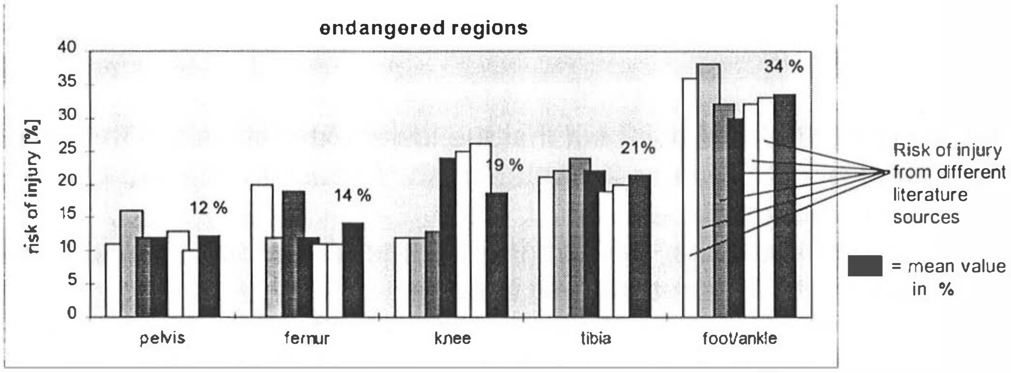


Figure 1: Injury risk from different regions of the lower extremities [1-6]

Figure 1 shows the risk of injury found in different literature sources. The first six columns assigned to one body region represent the percentage injury risk found in different literature sources. The last column with the percentage value above represent the mean value from these literature sources.

As one can see in Figure 1 the feet and the tibia are endangered most with totally more than 50% risk of injury.

Injuries to the lower extremities are not more serve than AIS 4 and so not directly life-threatening, but they can reduce the quality of life for the crash victim due to a high risk of permanent impairment. Especially injuries in the area of foot and ankle are most complex.

Moreover the rehabilitation process especially of foot and ankle injuries is very long lasting and expensive so that these types of injuries are related to very high social follow-up costs.

CRASHTESTS FOR EVALUATING INJURY MECHANISMS - Related to the results of Figure 1, PARS performed crash tests to identify injury mechanisms in the footwell in real crash tests. The aim of the investigation was to analyse the injury mechanisms as a function of crash test and crash severity. Therefore 3 crashtests were performed.

With the first two tests the influence of crash severity and car-package were investigated.

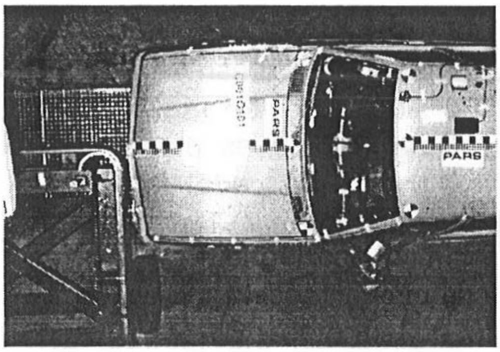


Figure 2: Test set-up for 50% offset crashtest

A 50 % offset crashtest was chosen. The tests were performed with two different car types and different crash severity:

1. Rear wheel drive at 40 km/h
2. Front wheel drive at 55 km/h

The rear wheel drive is usually a package of larger cars with the engine and the gear box placed longitudinal in the driving direction. So deformation of the footwell are caused by the deformation of the wheel well and the frame rail.

In front wheel drive cars the engine and the gear box are placed perpendicular to the driving direction, usually with little space between the rigid structures of the propulsion system and the footwell. So deformation of the engine compartment will directly result in intrusions of the footwell.

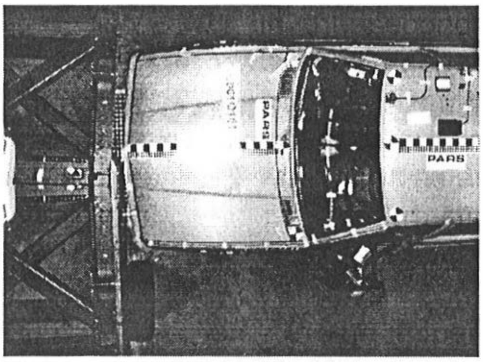


Figure 3: Crashtest with 100% overlap

In the second step PARS investigated the influence of crash type. Therefore another crash test at 56 km/h with a front wheel drive car was performed. This test was made as an 100% overlap test.

The crash tests were run with a HIII 50% driver dummy with the instrumented leg. With this the loads - forces and moments - in the upper and lower tibia can be measured. The acceleration in the foot was measured with additional sensors. The 45° dorsiflexion-range foot was used for all investigation. In the first two crash tests the soft-stop ankle was not used, because it was not available on market. In the third test which was made afterwards this soft stop ankle was used.

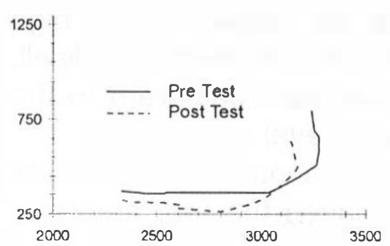


Figure 4: shape of footwell pre and post test

The toe pan and the wheelwell were instrumented with acceleration sensors to have a basis for the investigation in the following simulation study. The sensors were mounted in pairs of two - one on the top and one on the bottom of the toe pan and the wheelwell. This can be used to calculate the translational intrusion as well as the rotational intrusion level.

The footwell shape of the cars were measured pre and post test according to Figure 4 to verify the results of the acceleration sensors.

High Speed cameras were used to film the kinematics of the lower extremities during the crash test.

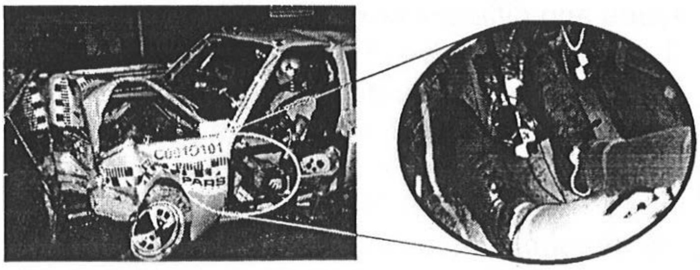


Figure 5: Placement of the feet during the crash

According to reality the right foot was placed on the break pedal in initial position (≈150 mm distance to toe pan) while the left foot was placed direct on the footrest at the wheelwell (see Figure 5).

INJURY MECHANISMS - The measured data of the dummy together with the high-speed films of the footwell were used to evaluate injury mechanisms and the source for the mechanisms. The following table gives a short summary about the injury mechanisms of the crash tests:

Table 1: Injury analysis of the crash tests in the foot area

No.	Configuration	left foot	right foot
1	40 km/h, 50% offset, rear wheel drive	• None	• High bending moment (dorsiflexion)
2	55 km/h, 50 % offset front wheel drive	• High bending moment (dorsiflexion) • High acceleration level	• High acceleration level
3	56 km/h, 100% overlap, front wheel drive	• High bending moment (dorsiflexion)	• High acceleration level • High tibia forces

In the crash-test No. 1 we found only a very slight intrusion level and only a slight rotation of the footwell. Besides from this we found high dorsiflexion loads in the right foot while the left foot is nearly uncritical. These loads were induced by the intruding brake pedal, because the forefoot was pushed backwards while the heel moved forward.

In test No. 2 we found high intrusions in the area of the footwell and a high rotation level. The left foot was pushed backwards by the intruding wheelwell. Moreover the wheelwell rotated highly, thus pushed the toes backward to the tibia. This resulted in a high dorsiflexion and acceleration level of the foot.
The loads on the right foot were not so critical, because the intruding instrument panel pushed back the femur and the tibia. This unloaded the foot area, but resulted in very high loads in the femur/knee region.

In test No 3 we obtained only small translational intrusions, but a high rotational intrusion level. This resulted in a high dorsiflexion level without any significant acceleration. In the right foot we obtained high tibia loads in correlation with high accelerations. This was a result of the contact between the forward moving foot and the intruding toe pan.

COMPARISON OF LITERATURE AND CRASHTESTS – To compare the mechanisms found in the three crash tests PARS performed a literature review. The aim of the investigation was to make sure, that the injury mechanisms of the crash tests correlate with the results of previous studies.
Morgan et al. [1991] found the following mechanisms:

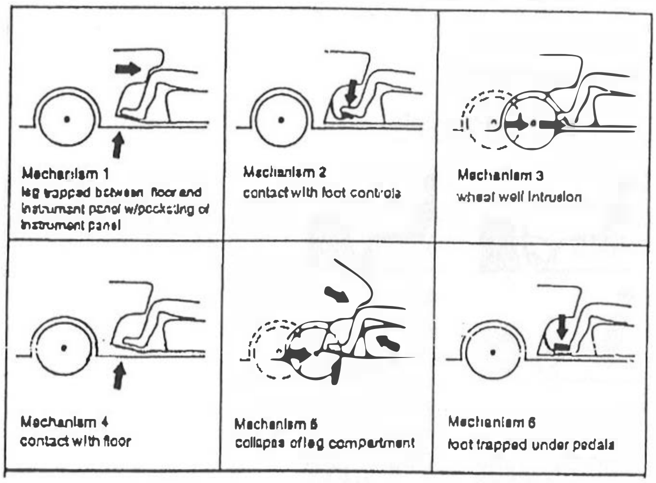


Figure 6: Injury mechanisms of the lower extremities

Figure 6 shows different injury mechanisms related to the lower extremities. The highest risk for injuries of the foot and ankle was found at the mechanisms 2 and 4 [Morgan].

The mechanisms 2 and 4 were also found in our study. Additional the mechanism 3 was found as a source for dorsiflexion. The effect of mechanisms 1, 5 and 6 was not obvious in our study.

Other literature sources shows that these mechanisms were identified as predominant injury mechanisms for the foot and ankle area.

Fildes et al. [1995] pointed out in their study a high injury risk for the tibia and foot. They pronounced dorsiflexion as well as in- and eversion as a major source for ankle and foot injuries. It was also mentioned that there was no significant relationship between the extent of intrusion and the lower limb fracture.
We also obtained high loads in our low severity crash, especially for mechanism No. 2, the contact with the foot controls.

According to Zeidler [1984] the high Δv between the forward moving foot and the intruding toe pan results in high loads in the foot and ankle area (impact shock syndrome). Fractures of the calcaneus, talus as well as tibia and fibula fractures seemed to be quite common to this mechanism.

Tailor et al. [1997] found out that 25% of all below knee injuries are related to a contact or a rolling off the foot pedal.

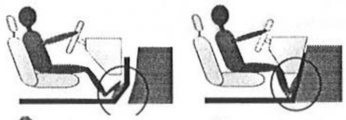
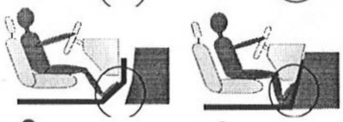
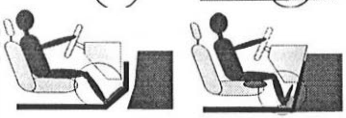
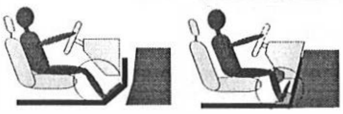
Tarriere, et al. [1995] made a review on biomechanical limits of the tibia, fibula, foot and ankle in dynamic load conditions. Fractures of the tibia/fibula can appear from 184 Nm (184-320 Nm), fractures of the calcaneus from 8 kN.
A comparison between dummy and cadaver tests were also performed during this study. The loads measured in the dummy's lower leg were much higher than the results from the cadaver tests.

CONCEPT DEVELOPMENT AND SIMULATION

To avoid the mechanisms found in literature and in our crash tests PARS has developed protection devices to prevent the occupant from sustaining injuries in the foot-area.

Four concepts were chosen with the help of an evaluation matrix. These concepts are:

Table 2: Concept matrix

No.	Concept	Principle
1	Energy absorbing foam	
2	Airbag in the footwell	
3	Airbag in the footwell and elevation of the femur	
4	Airbag in the footwell and kneebag	

To rank the concepts against each other a simulation model was built up. The model was validated to test No. 2 where the most serve intrusions were detected.

To rank the concepts against each other a simulation model was built up. The driver side model consisted of a MADYMO rigid body car environment and a belted MADYMO HIII dummy. The interaction of the dummy with the rigid environment was enabled by introducing force-deflection contact characteristics. The intrusion kinematics of the dashboard (translation only), the wheel well and the toe pan (translation and rotation) were prescribed.

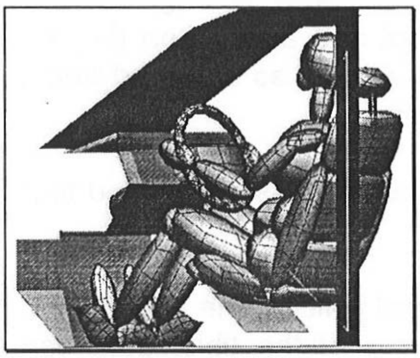


Figure 7: Set up of the simulation model

During this validation process the intrusion kinematics of the toe pan, the wheel well and the dashboard were adapted to the crash. The force-deflection contact characteristics were adapted as well. The belt model was taken from a simulation model that had been validated before and was therefore not modified.

After the validation the dummy loads and kinematics fitted well to those during crash test no. 2 as shown exemplary in Figure 8.

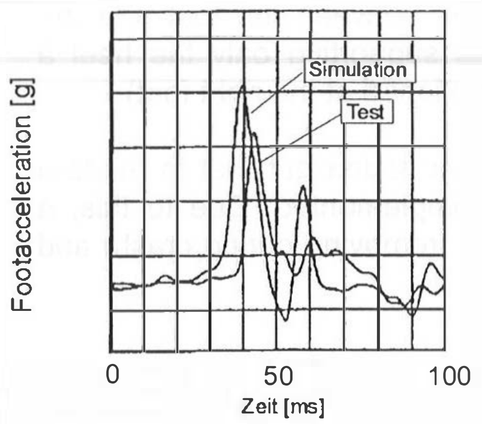


Figure 8: Example for correlation between crash and simulation

The implementation of the foot-airbag was made by coupling the MADYMO model with the PAM-CRASH airbag model. The airbag was put flat into the footwell. This means the package was not changed and the feet had still the same distance to the car structure.

To simulate a foam in the footwell the force-deflection contact characteristics of the toe pan and the wheel well were modified. The feet were enabled to penetrate deeper into the car structure. Due to this the initial distance between the foot and the car structure was not changed.

This made the results of the airbag and the foam comparable and made a ranking of the performance of the different protection devices possible.

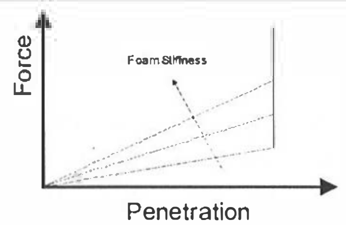


Figure 9: Foam Characteristic

During the optimisation process for the foam we compared different foam stiffness against each other. Foams were used from maximum reaction forces of 0.5 up to 1.5 kN. A linear penetration-force characteristic was chosen according to Figure 9.

The force applied to the heel of the foot is normally higher than the force on the forefoot. PARS also investigated the effect with different stiffness of the foam in the heel and forefoot area. It was found, that a foam with a thickness of 50 mm and a maximum reaction force of 1.0 kN in the heel and a softer foam in the forefoot area had the best results for the reduction of the loads.

For the airbag a size of a side airbag was chosen. The airbag is supporting the heel, not applying any loads on the forefoot and not coming into contact with the foot controls. For the airbag a serial side inflator was chosen. The cushion consists of dense, but not coated fabric without any additional venting. The shape of the airbag and the fixation in the footwell was optimised using extensive simulations.

The aim of the airbag in the footwell was:

For the right foot the airbag filled the initial gap between the foot and the toe pan. So the right foot was held nearly in the same position, preventing it from being slammed onto the toe pan. Supporting only the heel, the airbag was not applying any loads to the forefoot. Due to this the dorsiflexion loads were reduced by decreasing the dorsiflexion angle in the foot ankle. Moreover the foot was also stabilised in the cushion and can be prevented from slipping off the pedal, resulting in lower in-/eversion loads.

The left foot was pushed away from the foot rest in the beginning of the crash when no significant intrusions occurred. At the time the car structure was collapsing the airbag provided a damping cushion between the foot and the wheel well. Due to the fact that the airbag was supporting only the heel a reduction of dorsiflexion was also possible (as mentioned at the right foot).

The simulation showed the following results. It was found out that in modern cars devices for removing the brake pedal are implemented. Due to this, a simulation of the protection devices with removed (removing during crash) and non removed pedal was performed.

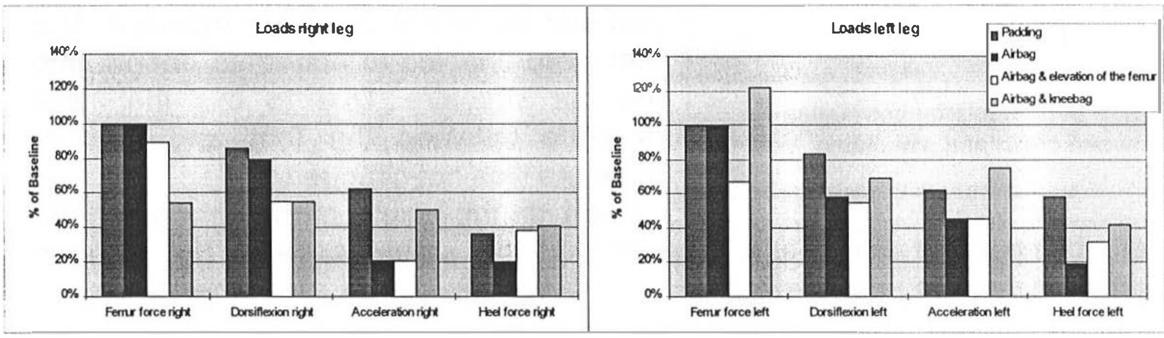


Figure 10: Comparison of protection devices with REMOVED pedal

The airbag in the footwell reduced the loads in the dummy's lower extremities better than the energy absorbing foam, especially the accelerations and the heel forces. The padding as well as the airbag were not able to reduce the femur forces.
With the two protection devices, the padding and the airbag in the footwell, a investigation with the brake pedal was performed.

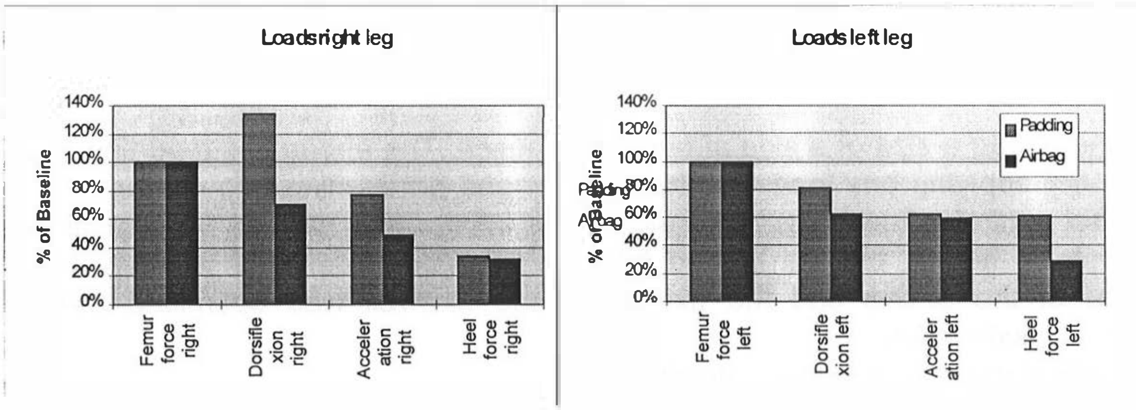


Figure 11: Comparison of the promising protection devices with NON REMOVED pedal

As it is shown in Figure 11 the airbag was able to reduce the loads in the dummy feet best. The padding was not able to protect the occupants foot on the brake pedal due to high dorsiflexion. This was a consequence of the penetration of the heel into the foam while the forefoot was held by the brake pedal. Due to this the dorsiflexion of the foot was increasing. With the use of an airbag the foot on the brake pedal can be protected. This was a result of the support of the heel from the airbag, because the heel had no contact with the toe pan, resulted in lower dorsiflexion and accelerations of the foot. So the airbag in the footwell seemed to be the most promising concept.

PERFORMANCE INVESTIGATION OF FOOT AIRBAG

With the airbag in the footwell PARS performed static deployment tests to optimise the fixing and to optimise the geometry of the airbag in the footwell. So the optimised Airbag got a special geometry for the left and the right foot. With this airbag it was possible to remove the feet from the intruding structures in the footwell. The static deployment tests showed that this can be done without the risk of adding critical loads to the feet. All loads applied to the feet are in the range from 10 % to 50 % of the biomechanical limits.

With the improved design PARS performed 2 sled tests to validate the protection performance of the airbag. These two tests - a baseline test and a test with an airbag in the footwell - were performed with the following boundary conditions:

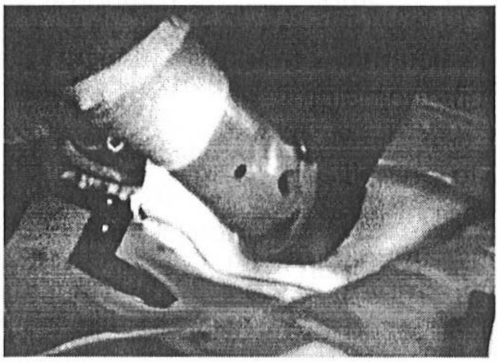


Figure 12: Support of the heel by an airbag

- static rotation of 85° of the toe pan
- no intrusion of the wheel well
- implementation of a break pedal in the footwell
- positioning of the right foot on the break pedal, left foot on wheel well

The rotation angle represented the post crash deformation of the worst case.

In the baseline test we obtained very high dorsiflexion. The right heel had a distance of 150 mm, the foot tip of 100 mm to the static intruded toe pan. In the left and right lower tibia, high accelerations in the right foot and moderate compression forces in the lower tibia in both feet. The right foot was generally loaded higher than the left foot due to the ΔV between the toe pan and the foot. With the use of an airbag in the footwell the loads in the right foot were reduced in all measuring points due to the support of the heel (see Figure 12).

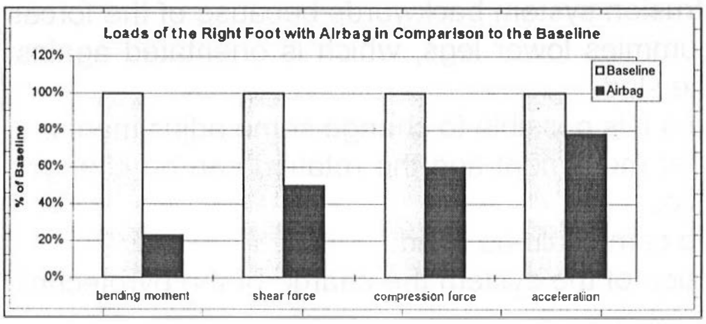


Figure 13: Loads of the right tibia/foot in the dynamic sled tests

Figure 13 shows the performance of the developed airbag in the footwell and the reduction of the loads.

TEST DEVICES TO SIMULATE A REPRODUCIBLE INTRUSION CHARACTERISTIC ACCORDING TO A CRASH TEST

As long as full scale crash tests are not reproducible for measuring loads in the footwell, a system which simulate this on a sled buck is required. The aim of this development was to create a intrusion system for the given injury mechanisms in the footwell.
This system reproduces the kinematics of the firewall in a car. With the test set-up static tests can be as well performed as sledtests. This system will be integrated in the reinforced car body. The dummy is placed in a seating-position according to the crash test.

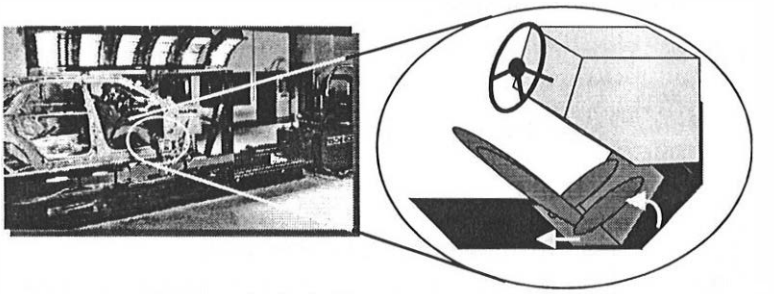


Figure 14: Footwell of sled buck with dynamic footwell intrusion system

The goal of the complete set-up is the reproduction of intrusion, which is a combination of linear and rotational acceleration.
The function is as follows:
The system is powered by a pyrotechnic unit with a pneumatic-cylinder. The load of the cylinder is applied through a piston-rod to the intrusion-sled. It is mounted on a shaft and this causes a linear movement in longitudinal direction (x-axis). The rotation of the firewall is produced by a curve-disc, which is assembled on a splineshaft. The shaft is driven on a gear wheel and a fixed gear rack. This is a connection between the linear movement and the rotation. The energy of the sled is absorbed by a deformation-tube. After the intrusion-movement is finished the system has to be fixed in the intruded position. Otherwise the sled acceleration would cause a shifting of the intrusion system backwards because of the forces applied to the system by the dummies lower legs, which is orientated against the acceleration movement of the sled.
In order to represent different cars it is possible to change some adjustments:

- The relation between the linear movement and the rotation can be changed by a different transmission ratio.
- Curve-discs with an geometric cam could be used.
- To achieve different acceleration of the system the charge of the pyrotechnic drive can be changed.
- The movement of the sled can be adjusted from 50 mm to 250 mm with a stopper.
- The position of the firewall before a crash can be fixed with a distance-holder in an area between 30° and 45°.
- The angle of rotation of the toe pan can be adjusted from 0° to 45°.

Accelerometers are mounted on the sled and on the foot-panel. Also the longitudinal movement of the intrusion-sled is measured. This data are used to compare the characteristic of the crash to the sled.

During the study we performed a comparison between one of the crashtests and the dynamic footwell intrusion system. A comparison between the crashtest and the sledtest is shown in Figure 15.

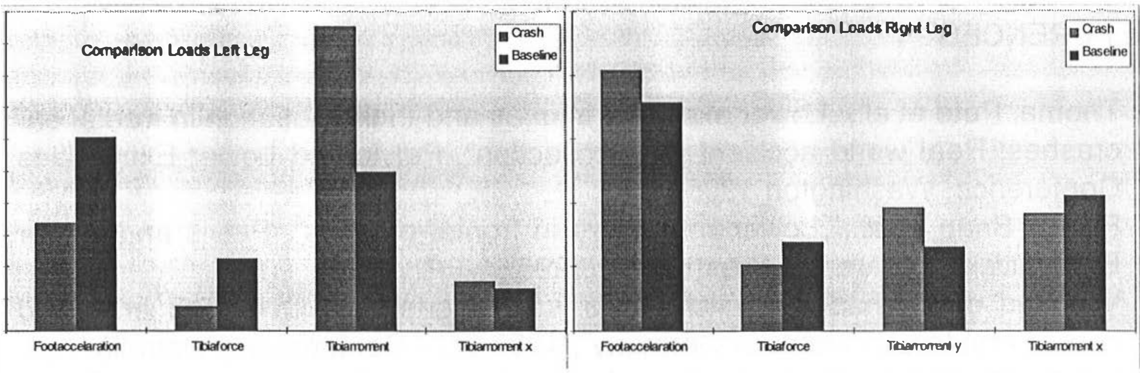


Figure 15: Comparison between a crash test and a sled test with dynamic footwell intrusion

As discussed above only one plane for both feet in our intrusion system is available today. Therefore we have to focus specially on one side – left or right foot. In this test the priority was to reproduce the loads on the right foot. The comparison between the crash and the baseline-sledtest shows that the loads applied to the right foot are reproduced nearly.
The loads in the left foot are because of using only one foot-panel for both feet different from the crash test.

SUMMARY AND CONCLUSIONS

During the accident research study it was found, that the foot/ankle region is the most severe injured region of the lower extremities in frontal crashes.
To evaluate injury mechanisms in the footwell and to design protection devices for the feet, PARS has performed crash tests to investigate the influence of crash type, car structure and crash severity.
With these information a simulation model was set up and validated to evaluate the protection potential of different techniques.
Protection devices were developed and ranked with the use of the simulation model.
The results showed, that although foam has quite a good performance protecting the foot against acceleration due to the intrusion, an airbag has substantial advantages, especially when the foot is placed on a brake pedal.
One of the main advantages is to reduce the dorsiflexion of the right foot in case the foot is placed on a pedal. This is the most likely situation, because more than half of the drivers apply the brakes before hitting the collision partner.

With static tests the airbag was characterised. It was shown that an unexpected or unnecessary deployment do not exceed 50% of the biomechanical loads
The protection function was investigated with sled tests and a reduction of the injury values up to 77% was proven.
The device for the dynamic footwell intrusion on the sled buck allows to perform sled tests with a reproducible intrusion characteristic.

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